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EXPERIMENTAL STUDY OF THE EFFECT OF BALL DIAMETER, ROTATING MASS AND INPUT GRAIN SIZE OF SILICA SAND ON THE EFFICIENCY OF MILLING IN VERTICAL VIBRATING MILL

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ABSTRACT

The Vertical vibrating mill is a new design of vibrating mills which are used to produce micro-powders, and nano-powders. This paper studies the effect of four different parameters (rotational speed, the milling media size (ball diameter), the input grain size, and the mass of the rotating mass) on both milling time and output grain size. The influence of several milling parameters such as ball diameter, motor rotational speed and rotating mass on milling time and output grain size of vertical vibrating mill was studied experimentally using laboratory data. The milling time and output grain size were determined using the above variables. The optimum condition of the silica sand milling that was obtained shows that the rotating mass is the most important parameter which affects milling time. It is also found that 1500 RPM of rotational speed with 16 mm ball diameter and 222 g rotating mass is the optimum condition to reach minimum milling time and minimum output grain size.

KEYWORDS: Rotating Mass, Silica Sand, Vibration, Milling Machine & Crashing Machine

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Original Article

INTRODUCTION

Industrial size reduction falls into two main groups: crushing and milling. Crushing which refers to the reduction in size of the large chunks to about 0.5 - 0.75in, diameter. This process is mostly a dry process, while milling on the other hand is the reduction in the material sizes to a micron or even nano-size range, and can be either wet or dry [1].

The main objectives of milling are obtaining the required particle sizes, to separate the desired materials from the ore, and to increase the surface area of the chemical reactions.

It is well known that the highest amount of energy consumption in the mining industry is size reduction operations which almost consume 50% of the mining plant energy. With the increase of energy and row materials costs, it is very important to improve the efficiency of mills, and since there are many parameters that can affect the milling process, it is important to study the effect of each parameter on the process [2 - 4].

In a previous study on a ball mill, it was found that 85% of the input energy was lost as heat, 14% of this heat was converted into kinetic energy, and only 1% of the energy had a benefit in grinding the ore, which means that any minor change in the mill efficiency will actually lead to a considerable improvement in the energy utilization [2 - 4].

It is important to find the optimum working conditions for the mill in order to increase the efficiency and eventually decrease the energy consumption [5].

The milling of silica sand can be a very good source of income to Jordan.

Silica sand has a large number of industrial applications depending on its characteristics such as: production of glass, ceramics, sandblasting and other abrasives, production of silicon and silicon carbide, pigments, ultra-high silica products in the electronic and fiber optic industries and water filtration [6].

White silica sand deposits are found exposed on the surface in south of Jordan. Deposits are found in the following locations: - Ras En Naqb area, Qa'Ed Disa area, Petra Ein El Biada area, Wadi Es Siq-Wadi Rakiya area and Al Jayoshia area [7].

Silica sand in Jordan is characterized by the following: Exposed on the surface, Low content of impurities and heavy minerals, Close to the Aqaba port, Huge Reserve, Easily accessible area [7].

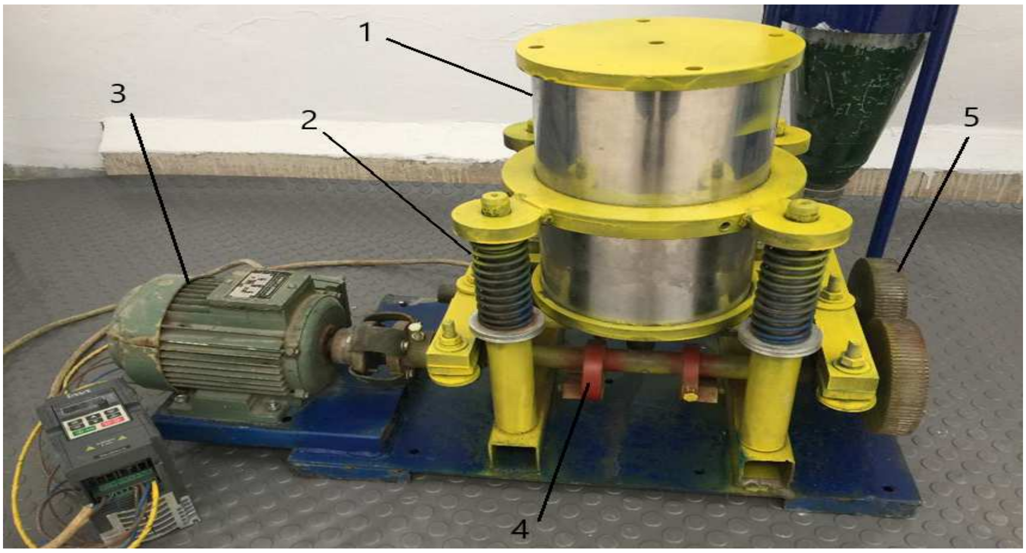
The Jordanian silica sand is considered a national treasure that was not utilized correctly up till now. Therefore, the Ministry of Energy and Mineral Resources (MEMR) welcomes local and international firms and investors that are interested in benefiting from the unlimited opportunities associated with Silica Sand [7].

During this study, a vertical vibrating mill (VVM) is used, and the effect of different parameters such as ball size, motor speed, and the vibration amplitude on the efficiency are shown.

EXPERIMENTAL SETUP

The Vertical Vibrating Mill (VVM) figure 1 consists of the vibrating chamber, four springs, milling media and two cam shafts.

When the two cams shaft rotate in opposite direction, the horizontal forces are canceled by each other and vertical component enhanced each other so the vibrating chamber goes up and down and makes the milling media hit each other where the sand will be between milling media [8, 9].



1: Vibrating Chamber, 2: Spring, 3: Electrical Motor, 4: Rotating Mass, 5: Gears.
Figure 1: The Experimental Setup of VVM.

THEORETICAL ANALYSIS

Rotating unbalanced weights transmit impulses to the mill chamber. The grinding is a result of the feed material getting between the grinding media and other grinding media or between the grinding media and the chamber surface. In horizontal vibrating mill, another main form of force which is the shear force occurs causing abrasion (friction) between the feed and the chamber surface which also leads to reduction in the grain size of the feed [8, 9].

Figure 2 shows the system of unbalance rotating mass of the vibrating machinery [8, 9], which is used in the experimental setup of VVM.

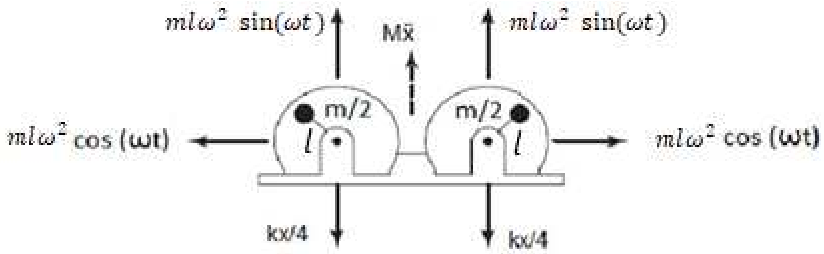


Figure 2: Unbalance Rotating Masses [9].

If the angular position of the masses is measured from a horizontal position, the total vertical component of the excitation is always given by:

$$F(t) = ml\omega^2 \sin(\omega t) \tag{1}$$

Where 1) *m:* rotating mass, 2) ω: angular velocity, 3) *l:* eccentricity, 4) *t*: time.

The equation of motion can be deriving by the usual procedure:

$$M\ddot{x} + kx = ml\omega^2 \sin(\omega t) \tag{2}$$

Where 1) M: vibrating chamber mass and balls mass, 2) *k:* spring constant

The solution of this equation will be identical by replacing m and F_0 by M and ($ml\omega^2$) respectively. We can express the solution as the following:

$$x_p(t) = X \sin(\omega t) \tag{3}$$

Where calculate the natural frequency using, $\omega_n = \omega = \sqrt{\frac{k}{M}}$

Calculate the amplitude using $X = \frac{ml\omega^2}{k - M\omega^2}$

Where the multiplication by 2 is due to having 2 assets of opposite rotating masses:

$$X = \frac{\omega^2}{\mathrm{Keq} - \mathrm{M}\,\omega^2} * 2\ \mathrm{m}l \tag{4}$$

Where the equivalent stiffness is: $Keq = 4\,k$

The equation of spring design: $k = \frac{Gd^4}{8\,D^3\,n}$....[10]

Where *G:* modulus of rigidity, *D:* mean coil diameter, *d:* wire diameter, *n:* Numbers of coil turns.

RESULTS AND DISCUSSIONS

The machine is filled with ball shaped milling elements that have the diameter of 18 mm. The machine has 3 stages, each stage contains 4.5 kg of balls so. The empty machine weighted 34.1 kg and the total weight of the machine with the balls is 47.6kg.

Four identical rotating masses, 170 g each are mounted on the two shafts. Two different sizes of sand grains (0.17 and 1.7mm) were used, 500 g for each size. Three rotating speeds were applied on the machine (1250, 1333 and 1500).

The time taken for the sample to be milled and the output grain size were measured. Two important sizes of the output were identified, the output size that had the largest amount and the smallest output size.

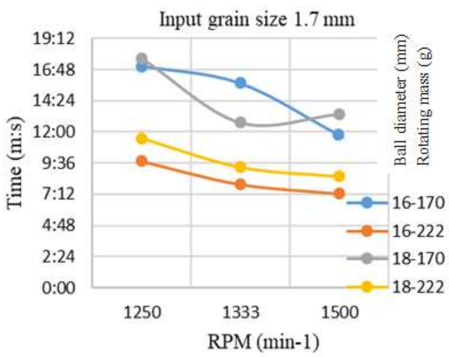
Using these two sizes and their masses four variables were identified, the reduction rate [RR]; the ratio between the input grain size and the size of the grains that had the largest amount, the reduction rate by mass [RR by mass]; the ratio between the input mass and the mass of the grains that had the largest mass, the maximum reduction [MR]; the ratio between the input grain size and the smallest output size, and the maximum reduction by mass[MR by mass] which is the ratio between the input mass and the smallest grain size mass .

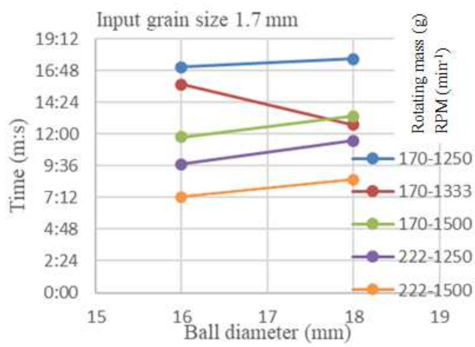
The rotating masses were then replaced with four other masses each one is 222 g. and the speed varied between (1250, 1333 and 1500 rpm).

For each input size, three samples 500 g each were used, milling time and the output grain size were measured. RR, MR, RR by mass and MR by mass were calculated.

The milling elements were then replaced with another size of steel balls 16 mm, each stage was filled with 3.29 kg of balls and the machine weighted 43.97 kg in total with the rotating mass is still 222 g. The previous procedure was repeated, milling time and the output grain size were measured and RR, MR, RR by mass and MR by mass were calculated.

With the milling elements are still 16 mm balls, the rotating masses were replaced with the four 170 g masses. Milling time and output grain size were measured and RR, MR, RR by mass and MR by mass were calculated for each rotating speed.



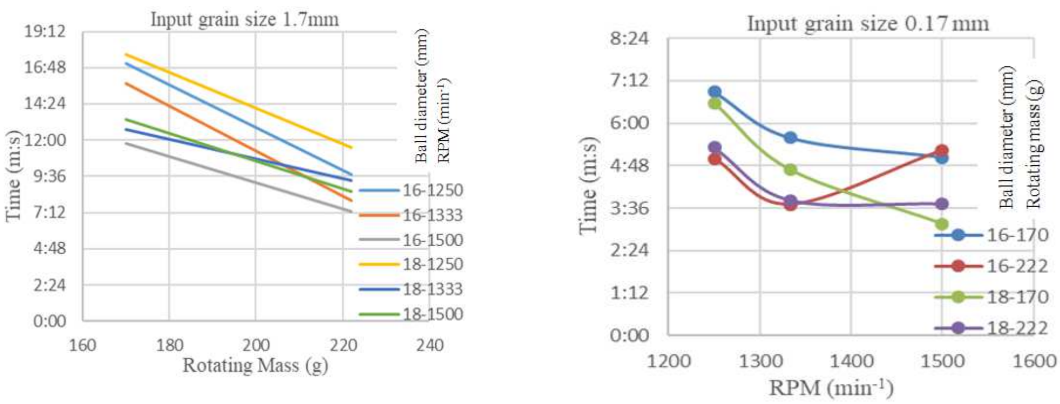


(A) (B)

Figure 3: (A) Milling Time Versus Rotational Speed for 1.7 mm Input Grain Size. (B) Milling Time Versus ball Diameter for 1.7 mm Input Grain Size.

Varying the rotational speed has different effects depending on the ball's diameter and the mass of the rotating mass. As shown in figure 3(A), for 222 g rotating mass the results are quite similar for both 16 and 18-mm diameters, the milling time decreases severely between 1250–1333 rpm. Hence, the milling time is decreased. For 16-mm, 170g the milling time decreases as the rotating speed increases. It reaches a minimum milling time of 12:30m at 1333 rpm for the sample where 18 mm balls and 170g rotating mass where used.

The time versus ball diameter relation is shown in figure 3(B). It is noticed that the milling time increases as the ball diameter increases for all samples except for the sample 170g rotating mass-1333 rpm where the milling time noticeably decreases.



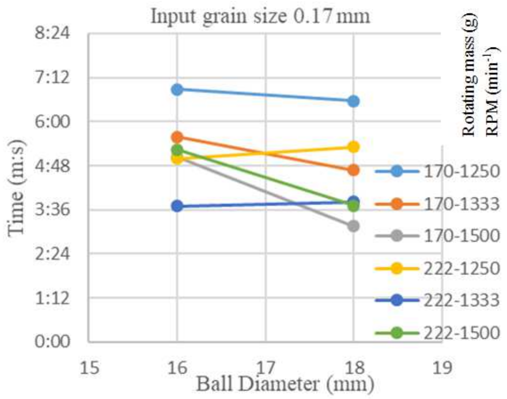
(A) **(B)**

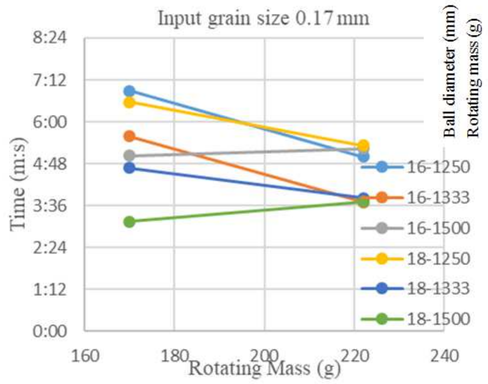
Figure 4: (A) Milling Time Versus Rotating Mass for 1.7 mm Input Grain Size. (B) Milling Time Versus Rotational Speed for 0.17 mm Input Grain Size.

Increasing the mass of rotating Mass will decrease the milling time for all samples in figure 4(A), but it is clearly seen for the samples where the smaller ball diameter is used.

In figure 4(B) increasing the rotational speed while using 170 g rotating mass has similar effect on milling time for both 16 and 18-mm balls, where the milling time is reduced as the rotational speed increases. But this reduction is higher for 18 mm balls. For the sample where 16 mm balls and 222g rotating mass were used, the milling time is decreased until the rpm reaches 1333 min^{-1} and then the milling time increases as the rpm increases. For the sample where 18mm balls and 222g mass were used the milling time decreases until the speed reaches 1333 min^{-1} were the milling time remains the same.

Figure 5(A) shows that the milling time slightly decreases for most samples as the milling balls diameter increases except for 222g rotating mass, 1250rpm and 222g rotating mass, 1333rpm where milling time increases as the diameter increases for both of the samples.

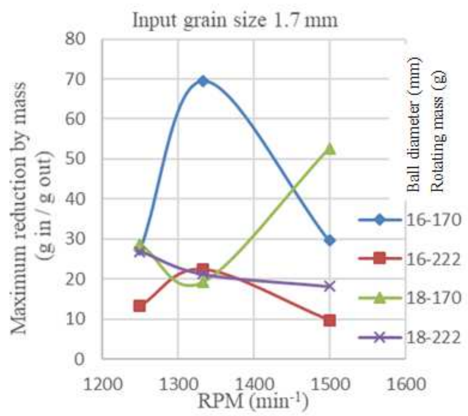


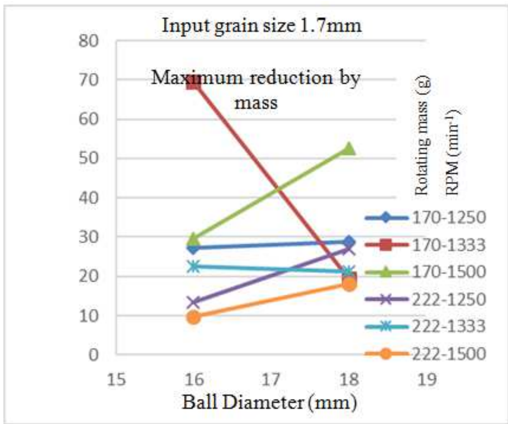


(A) (B)

Figure 5: (A) Milling Time Versus Ball Diameter for 0.17 mm Input Grain Size. (B) Milling Time Versus Rotating Mass for 0.17 mm Input Grain Size.

In figure 5(B), the milling time decreases as the rotating mass increases for both 16 and 18-mm ball at 1250 and 1333 rpm and it has the opposite effect at 1500 rpm where the milling time starts to increase as the mass of the rotating mass increases.



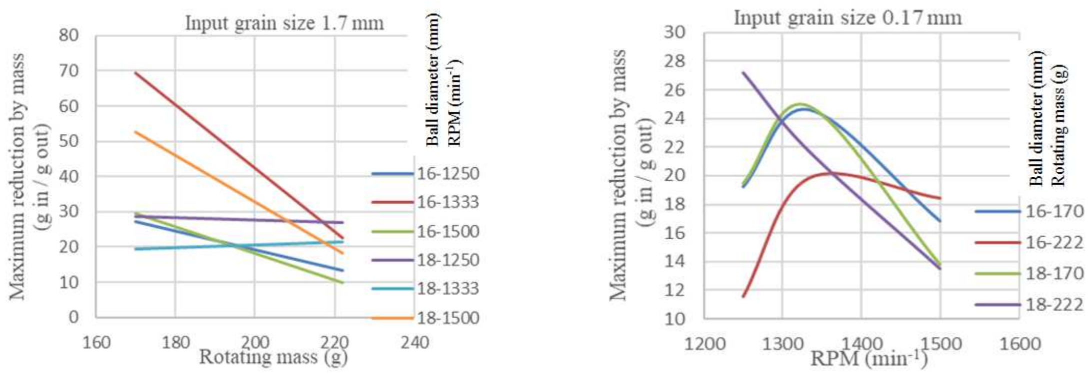


(A) (B)

Figure 6: (A) Maximum Reduction by Mass Versus Rotational Speed for 1.7 mm Input Grain Size. (B) Maximum Reduction by Mass Versus Ball Diameter for 1.7 mm Input Grain Size.

Figure 6(A) shows that as the rotational speed increases, the maximum reduction by mass also increases for most of the samples until the rotational speed exceeds 1333 min^{-1} where the maximum reduction by mass begins to decrease. For the case of 18mm diameter, 222g rotating mass maximum reduction by mass decreases as rotational speed increases. For the sample of 18mm diameter, 170g rotating mass, as the rotational speed increases, a drop in the maximum reduction by mass occurs until the rotational speed exceeds 1333 min^{-1} where the maximum reduction by mass begins to increase again.

It is clearly seen in figure 6(B) that while changing the ball diameter from 16mm to 18mm the maximum reduction by mass is highly increased. In the sample 170g rotating mass, 1333 rpm changing the ball diameter from 16mm to 18mm decreases the maximum reduction by mass (that means Insufficient force to throw balls). For the sample 222g rotating mass, 1333 rpm a slight decrease in the maximum reduction by mass occurs.



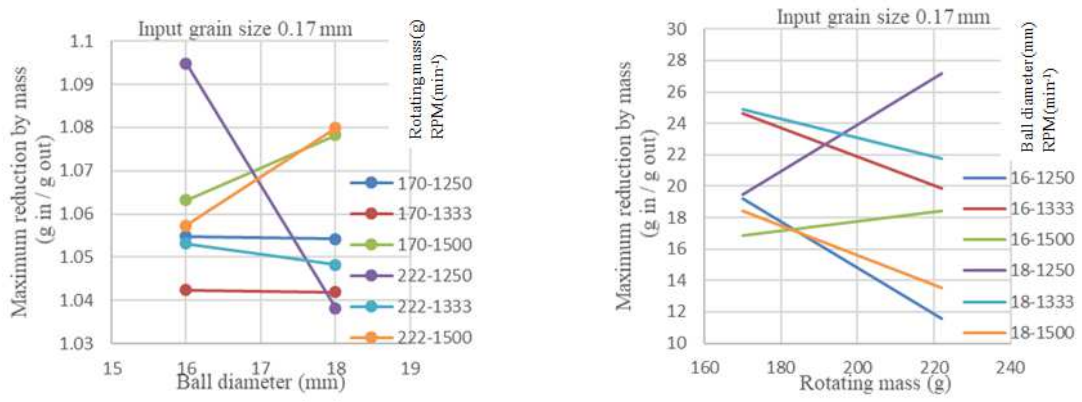
(A) **(B)**

Figure 7: (A) Maximum Reduction by Mass Versus Rotating Mass for 1.7 mm Input Grain Size. (B) Maximum Reduction by Mass Versus Rotational Speed for 0.17 mm input Grain Size.

As shown in figure 7(A) increasing the rotating speed tends to cause a decrease in the maximum reduction by mass, but for 18 mm balls at 1250 rpm the maximum reduction by mass slightly decreases. And 18 mm balls at 1333 rpm the maximum reduction by mass slightly increases.

Figure 7(B) shows as the rotational speed increased, an increase in the maximum reduction by mass occurs for most of the samples until the rotational speed exceeds 1333 where the maximum reduction by mass begins to decrease again. But for the sample with 18mm diameter and 222g rotating mass maximum reduction by mass only decreases.

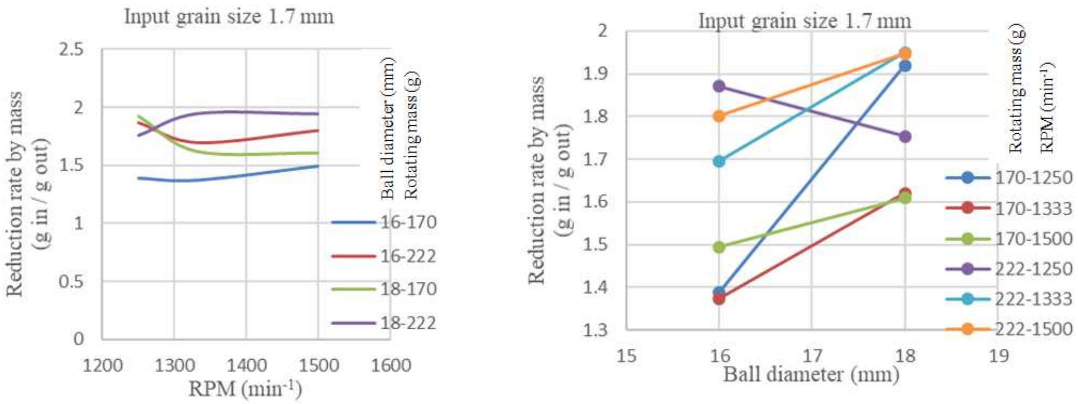
In figures 6(B) and 8(A) seen that while changing the ball diameter from 16mm to 18mm, a decrease in the maximum reduction by mass occurs (that means Insufficient force to throw balls such as case 222g rotating mass, 1250rpm). In some cases such as 222g rotating mass, 1500 rpm, and 170g rotating mass, 1500 rpm changing the ball diameter from 16mm to 18mm highly increases the maximum reduction by mass.



(A) **(B)**

Figure 8: (A) Maximum Reduction by Mass Versus Ball Diameter for 0.17 mm Input Grain Size. (B) Maximum Reduction by Mass Versus Rotating Mass for 0.17 mm Input Grain Size.

Increasing the rotating mass causes a decrease in the maximum reduction by mass, but for 18 mm balls at 1250 rpm, and 16 mm balls at 1500 rpm the maximum reduction rate tends to increase, figure 8(B).

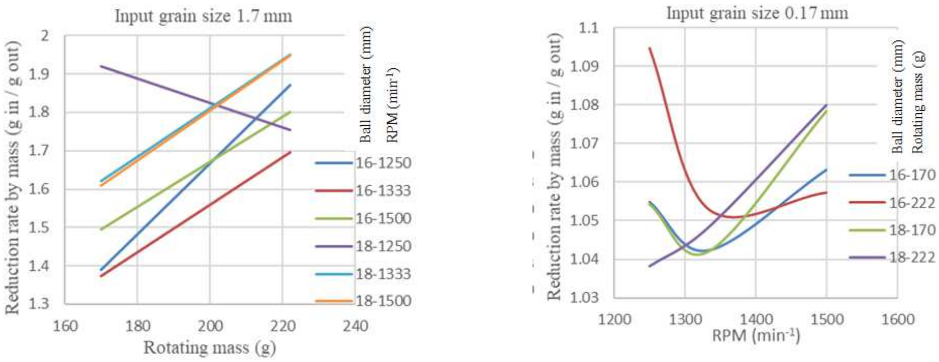


(A) **(B)**

Figure 9: (A) Reduction Rate by Mass Versus Rotational Speed for 1.7 mm input Grain Size. (B) Reduction Rate by Mass Versus Ball Diameter for 1.7 mm Input Grain Size.

Figure 9(A) shows that as the rotational speed increases, the reduction rate by mass tends to decrease until the rotational speed reaches 1333 min^{-1} where it starts to increase again for most samples. For the sample 18mm ball diameter, 222g rotating mass the reduction rate by mass increases till the speed reaches 1333 and then reduction rate by mass decreases slightly.

From the reduction rate versus ball diameter graph shown in figure 9(B), it is noted that while in some cases such as (170g rotating mass, 1250 rpm) changing the ball diameter from 16mm to 18mm highly increases the reduction rate by mass, some other cases lead to a slight increase in the reduction rate by mass such as (170g, 1500 rpm) and in another case (222g, 1250 rpm) a decrease in the reduction rate by mass occurs.



(A) **(B)**

Figure 10: (A) Reduction Rate by Mass Versus Rotating Mass for 1.7 mm Input Grain Size. (B) Reduction Rate by Mass Versus Rotational Speed for 0.17 mm Input Grain Size.

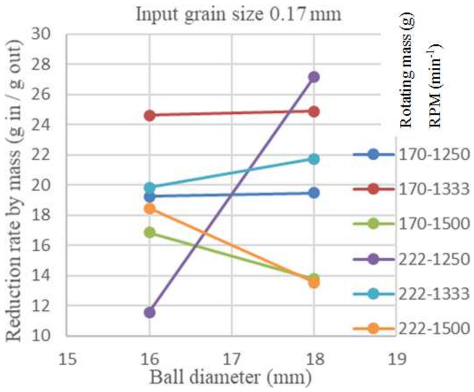
Increasing the rotating mass would most likely lead to an increase in the reduction rate as seen in figure 10(A), but when working with 18 mm balls at 1250 rpm the reduction rate tends to decrease such as figures 6(B) and 8(A).

As the rotational speed increases, a drop in the reduction rate occurred for most of the samples until the rotational speed exceeds 1333 min^{-1} where the reduction rate begins to increase again (figure 10(B)). But for the case of 18mm diameter, 222g rotating mass reduction rate only increases.

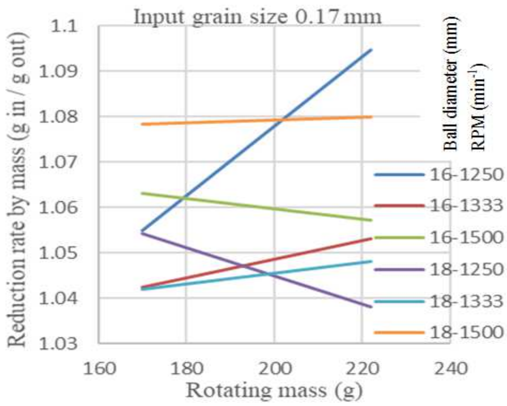
From the reduction rate versus ball diameter graph shown in figure 11(A), it is clearly seen that while in some cases such as 222g rotating mass, 1250 rpm changing the ball diameter from 16mm to 18mm highly increases the reduction

rate, some cases lead to a slight increase in the reduction rate such as 170g rotating mass, 1250 rpm and in other cases 222g rotating mass, 1500 rpm and 170g, 1500 rpm a decrease in the reduction rate occurs.

Figure 11(B) shows that as the mass of the rotating masses increases, the reduction rate increases in most cases, at 18mm ball diameter, 1250 rpm and 16mm ball diameter, 1500 rpm the reduction rate decreases.

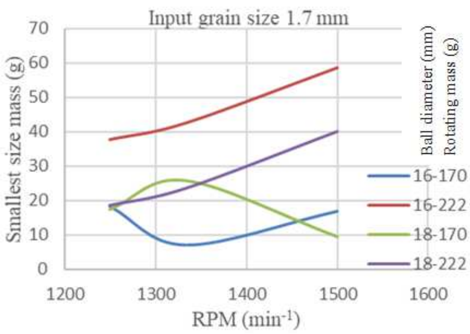


(A)

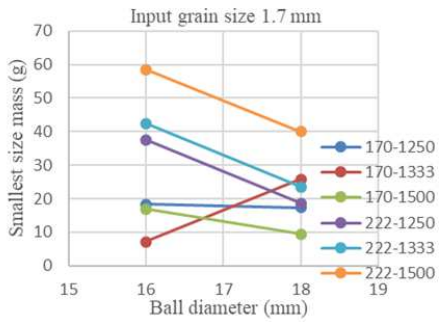


(B)

Figure 11: (A) Reduction Rate by Mass Versus Ball Diameter for 0.17 mm Input Grain Size. (B) Reduction Rate by Mass Versus Rotating Mass for 0.17 mm Input Grain Size.



(A)

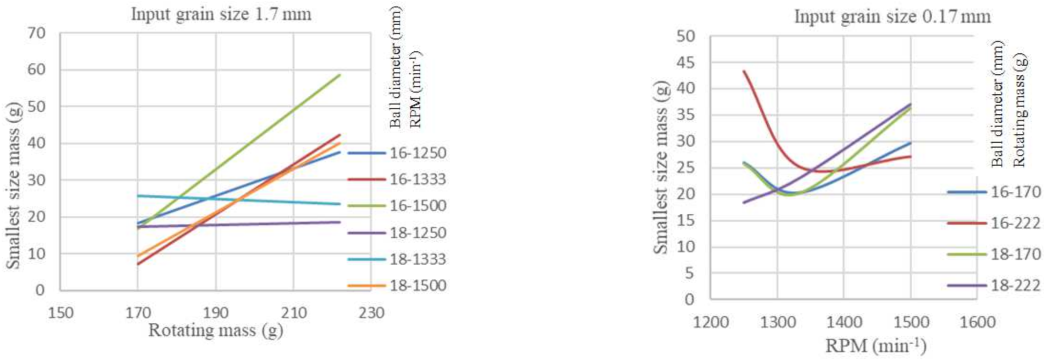


(B)

Figure 12: (A) Smallest Size Mass Versus Rotational Speed for 1.7 mm Input Grain Size. (B) Smallest Size Mass Versus Ball Diameter for 1.7 mm Input Grain Size.

Figure 12(A) shows, as the rotational speed increases, increase in the smallest size mass occurres for 222 g rotating mass in each ball diameter. But for 16mm diameter, 170g rotating mass, smallest size mass decreases until the rotational speed exceeds 1333 min^{-1} where it increases again. For 18mm diameter, 170g rotating mass, smallest size mass is increased until the rotational speed exceeded 1333 min^{-1} where it begins to decrease again.

As shown in figure 12(B), while changing the ball diameter from 16mm to 18mm, a decrease in the smallest size mass occurred for most samples. For 170g rotating mass, 1333 rpm changing the ball diameter from 16mm to 18mm highly increases the smallest size mass.

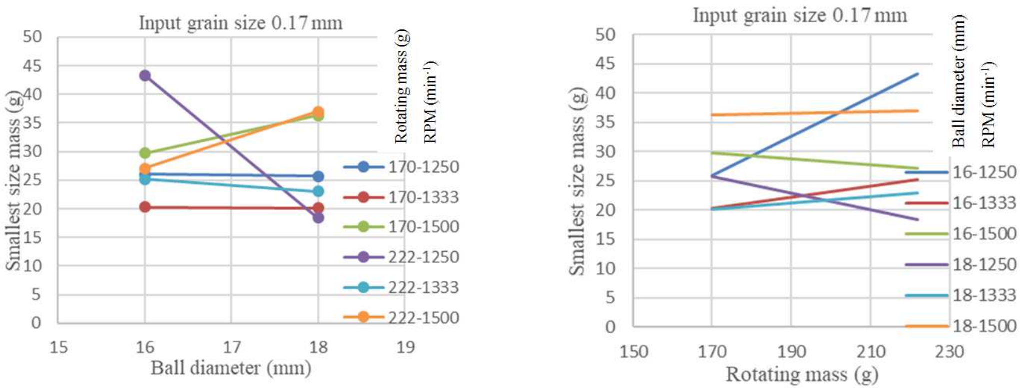


(A) (B)

Figure 13: (A) Smallest Size Mass Versus Rotating Mass for 1.7 mm Input Grain Size. (B) Smallest Size Mass Versus Rotational Speed for 0.17 mm Input Grain Size.

Increasing the rotating mass causes an increase in the smallest size mass, but for 18 mm balls at 1333 rpm the smallest size mass tends to slightly decrease (figure 13(A)).

Figure 13(B) shows that As the rotational speed increases, the smallest size mass decreases for most of the samples, until the rotational speed exceeds 1333 where the smallest size mass starts to increase again. For the sample 18mm diameter, 222g rotating mass the smallest size increases as rotational speed increases.



(A) (B)

Figure 14: (A) Smallest Size Mass Versus Ball Diameter for 0.17 mm Input Grain Size. (B) Smallest Size Mass Versus Rotating Mass for 0.17 mm Input Grain Size.

In figure 14(A), it is well noticed that while changing the ball diameter from 16mm to 18mm, decrease of the smallest size mass occurs for the sample 222g rotating mass- 1250 rpm. And for 170g rotating mass, 1500 rpm and 222g rotating mass, 1500 rpm changing the ball diameter from 16mm to 18mm increases the smallest size mass. For 170g rotating mass as 1250 and 1333rpm and 222g rotating mass at 1333 rpm the smallest size mass is almost constant.

In figure 14(B), increasing the rotating mass causes an increase in the smallest size mass for 16 mm ball diameter at 1250 and 1333 rpm and 18 mm ball diameter at 1333 rpm, but for 18 mm ball diameter at 1250 rpm and 16 mm ball diameter at 1500 rpm it decreases. For 18 mm balls at 1500 rpm the smallest size is almost constant.

Figures (15, 16) show the relation between output size and its output mass percentage, the optimum condition for each output size can be obtained from these figures. Hence, the operator can estimate how much input mass and the best condition that should be used to produce the required mass of the required size.

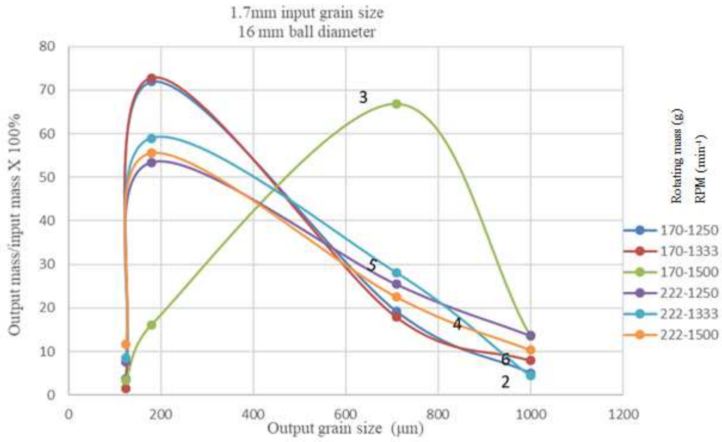


Figure 15: Output Mass Percentage Versus Output Grain size for 1.7 mm Input Grain Size and 16 mm Ball Diameter

In figure 15, the variation of the mass of each output grain after variating the rotational speed for 1.7 mm input grain size and 16 mm ball diameter it is shown. For most of the samples, the mass of the output is at highest for the output size of 0.18mm whereas the mass for the bigger sizes decreases. For the sample 170 g rotating mass and 1500 rpm the largest output mass was for 0.71 mm.

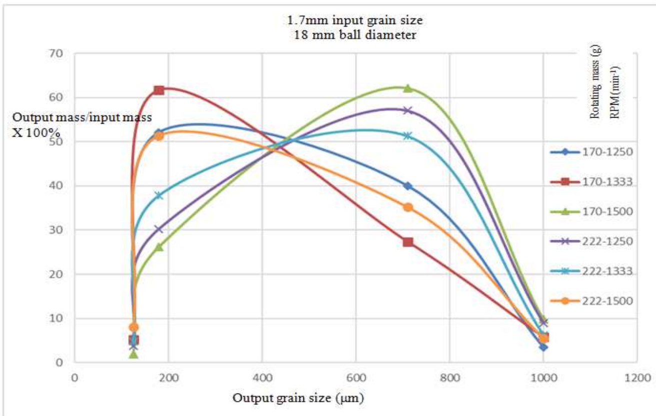


Figure 16: Output Mass Percentage Versus Output Grain Size for 1.7 mm Input Grain Size and 18 mm Ball Diameter.

In figure 16, 1.7mm input grain size, 18 mm ball diameter, at output grain size 125 µm the sample (222g, 1500rpm) has the highest Output mass percentage. Whereas for the output grain size 180 µm the sample (170g, 1333rpm) has the highest Output mass percentage and (170g, 1500rpm) has the lowest Output mass percentage. For output grain size 710 µm the sample (170, 1500rpm) has the highest Output mass percentage and (170g, 1333rpm) has the lowest Output mass percentage. For output grain size 1000 µm all of the samples have the same ratio of Output mass percentage. At range of 410 µm to 430 µm all sample have the same output mass percentage.

CONCLUSIONS

Two sizes of the sand grains were taken into consideration which are 1.7 and 0.17 mm. In each experiment, 0.5 kg of silica sand were fed into the machine. Another variable of interest that could affect the milling process is the milling ball size. In this category, two sizes of steel balls 18 and 16 mm have been chosen to be the grinding medium. Varying the rotational speed also affected the output grain size. So, speeds of (1250, 1333, 1500) rpm were chosen for the experiments two masses were taken to act as the rotating mass (170g and 222 g).

Several variables have been measured in these experiments such as output sand grain size and milling time. For most cases as the rpm increases, the milling time decreases and as the rotating mass increases the time decreases. As shown previously in the results, for input grain size of 0.17 the minimum output size was 90 µm and the largest size of the output is 125 µm. For 1.7 mm input grain size, the variables have minimum output grain size mostly at 125 µm with some samples having the minimum output size of 1000 µm. The output size that has the largest amount also varies with some samples at 180 µm and others at 710 µm.

Maximum reduction which is the ratio between the input grain size and the smallest output size was calculated in two ways; the ratio of sizes, and then the ratio between masses of the input mass and the smallest size mass. The ratio between sizes was almost constant for the input of 1.7 it had only two values (13.6 and 1.7) since samples' smallest output was (1.25 and 1000 µm), and for the 0.17 input grain size the maximum reduction for all samples was 1.9 because the smallest output size for all samples was 90 µm.

As for the ratio of masses both input grain sizes have different results when varying the rotational speed, the rotating mass and the size of the milling elements.

The last variable that was calculated is the reduction rate that was also obtained by two methods; first method was the ratio between the input and output grain size that had the largest amount, were all the samples of 0.17 input size, had the value of 1.4, but, for the samples with 1.7 input size had two values of (9.4 and 2.4). The second method was calculating it as a ratio between masses, and here both of the input grain sizes showed different results when varying the RPM, the rotating mass and the milling elements size.

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